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Integrated Acoustooptic Device Modules for Optical Information Processing

Final Technical Report

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The general objectives of this AFOSR-sponsored research program are conception, experimentation and realization of new and novel guided-wave AO device modules in $LiNbO_3$ and GaAs with applications to wideband multichannel optical information processing, and study of relevant physical mechanisms. All objectives have been accomplished.

During the first two and a half program years (September 1, 1985 to February 28, 1988) the following major accomplishments were made:

1. Analysis on guided-wave acoustooptic Bragg diffraction in a GaAs waveguide,

2, Establishment of design procedures and fabrication steps for construction of miniaturized GaAs AO Bragg cells at the frequency range of 300 to 900 MHz,

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3. Development of titanium-indiffusion proton-exchange (TIPE) technique for fabrication of single-mode microlenses and lens arrays in $LiNbO_3$ planar waveguides,

4. Conception and realization of TIPE microlens-based hybrid-integrated optic AO modules in $LiNbO_3$ channel-planar composite waveguides, and demonstration of their applications in optical systolic array processing and computation such as matrix-vector and matrix-matrix multiplications,

5. Establishment of an ion-milling facility (through the sponsorship of DOD/AFOSR Research Instrumentation Program) for formation waveguide microlenses and lens arrays, and diffraction gratings,

6. Realization of GHz guided-wave AO Bragg cells in GaAs,

7. Conception and realization of monolithic-integrated AO and electrooptic (EO) modules in GaAlAs compounds waveguides, and applications to optical computing and signal processing, and

8. Realization of hybrid-integrated AO and EO modules together with the TIPE lenses in $LiNbO_3$ composite waveguides, and applications to optical computing and signal processing.

Since the above accomplishments have been described in two Interim Scientific Reports and one Final Technical Report, they will not be repeated here. In this Final Technical Report, the major accomplishments that were made in the last program year (March 1, 1988 to September 30, 1989) are presented. The accomplishments of the last program year are listed as follows:

9. Realization of Single-Mode TIPE Microlenses and Lens Arrays in $LiNbO_3$ Waveguide and High-Packing Density Multichannel Integrated Optic Modules

10. In-Depth Analysis on Guided-Wave Acoustooptic Bragg Diffraction in ZnO-GaAs Composite Waveguides

11. Realization of High-Performance GaAs Guided-Wave Acoustooptic Bragg Cells at GHz Frequencies

12. Formation of Microlenses and Lens Array in GaAs Waveguide Using Ion-Milling

Detailed descriptions of the progresses and the achievements are given in the publications listed in Sections III and IV of this report.

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Final Technical Report

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I. INTRODUCTION AND ACHIEVEMENTS OF EARLIER PROGRAM YEARS

Guided-Wave Optics, or more commonly called Integrated Optics, is an interdisciplinary endeavor which concerns basic studies, new device concepts, miniaturization and integration of optical and optoelectronic components such as lasers, modulators, switches, lenses, prisms, couplers, detectors, etc., in a common substrate to perform a variety of scientific and engineering functions. Similar to the prevalent integrated electronic circuits, the ultimate integrated optic circuits or modules are expected to possess advantages over their discrete bulk counterparts. Some of the advantages are smaller size and lighter weight, wider bandwidth, lesser electrical drive power requirement, greater signal accessiblity, higher degree of integratability, potential for batch fabrication, and ultimate reduction in cost. In fact, a variety of guided-wave electrooptic (EO) and acoustooptic (AO) devices and modules have been studied and developed using mostly the $LiNbO_3$ and GaAs substrates. Most recently, magnetostatic waves-based guided-wave magnetooptic Bragg cells (initiated and explored through an earlier AFOSR Grant) with electronically tunable carrier frequency at microwave frequenices were realized at this principal investigator's laboratory. Such devices and modules have demonstrated some of the aforementioned advantages and are expected to provide unique applications in future single-mode optical fiber communication, and integrated optic signal processing and computing systems.

The general objectives of this AFOSR-sponsored research program are conception, experimentation and realization of new and novel guided-wave AO device modules in $LiNbO_3$ and GaAs with applications to wideband multichannel optical information processing, and study of relevant physical mechanisms. All objectives have been accomplished.

During the first two and a half program years (September 1, 1985 to February 28, 1988) the following major accomplishments were made:

1. Analysis on guided-wave acoustooptic Bragg diffraction in a GaAs waveguide,
2. Establishment of design procedures and fabrication steps for construction of miniaturized GaAs AO Bragg cells at the frequency range of 300 to 900 MHz,
3. Development of titanium-indiffusion proton-exchange (TIPE) technique for fabrication of single-mode microlenses and lens arrays in $LiNbO_3$ planar waveguides,
4. Conception and realization of TIPE microlens-based hybrid-integrated optic AO modules in $LiNbO_3$ channel-planar composite waveguides, and demonstration of their applications in optical systolic array processing and computation such as matrix-vector and matrix-matrix multiplications,
5. Establishment of an ion-milling facility (through the sponsorship of DOD/AFOSR Research Instrumentation Program) for formation waveguide microlenses and lens arrays, and diffraction gratings,
6. Realization of GHz guided-wave AO Bragg cells in GaAs,
7. Conception and realization of monolithic-integrated AO and electrooptic (EO) modules in GaAlAs compounds waveguides, and applications to optical computing and signal processing, and
8. Realization of hybrid-integrated AO and EO modules together with the TIPE lenses in $LiNbO_3$ composite waveguides, and applications to optical computing and signal processing.

Since the above accomplishments have been described in two Interim Scientific Reports and one Final Technical Report, they will not be repeated here. In this Final Technical Report the major accomplishments that were made in the last program year (March 1, 1988 to September 30, 1989) are presented.

II. Progress and Achievements During Last Program Year

A summary of the major accomplishments of the last program year now follows.

9. Realization of Single-Mode TIPE Microlenses and Lens Arrays in $LiNbO_3$ Waveguide and High-Packing Density Multichannel Integrated Optic Modules

The titanium-indiffusion proton-exchange (TIPE) technique devised during earlier program years by us for construction of single-mode microlenses and lens arrays was further studied and developed. The successful fabrication of high-quality microlens arrays has enabled realization of a variety of high-packing density multichannel integrated optic (IO) modules with applications to communications, RF signal processing, and computing (See papers #1, 2, and 3 of Sect. III). For example, the modules were used to perform programmable correlation of binary sequences.

A novel technique for efficient and simultaneous excitation of the channel waveguide array that greatly facilitated convenient testing and applications of such multichannel IO modules was also devised (paper 4).

10. In-Depth Analysis on Guided-Wave Acoustooptic Bragg Diffraction in ZnO-GaAs Composite Waveguides

As indicated in Sect. I, we had earlier carried out an analysis on guided-wave AO Bragg diffraction in GaAs waveguides. As a continuation we extended the analysis to the waveguide structures that include a ZnO overlayer. This composite waveguide structure is of great practical importance because it eliminates the complicated processes of creating taper ZnO layers for excitation and detection of the SAWs as well as the resulting insertion losses. This analysis takes into account the detailed distributions of both the guided-optical modes and the SAWs in the ZnO and the GaAs layers. Families of plots for diffraction efficiency and frequency response have been generated using computer calculation with the thickness of the ZnO and the GaAs layers, the optical wavelength, and the waveguide mode as parameters. Thus, this latest and complete analysis has established the key design parameters and design procedures for realization of high-performance guided-wave GaAs AO Bragg cells. A paper is being prepared for publication (paper #5).

11. Realization of High-Performance GaAs Guided-Wave Acoustooptic Bragg Cells at GHz Frequencies

It is desirable to realize AO Bragg cells with their center frequencies, bandwidth, and efficiency as high as possible. As stated in item 10, further theoretical analysis together with computer calculations have established the procedures for optimal design of the GaAs Bragg cells. Improvement in our in-house fabrication facility enabled realization of wideband high-efficiency AO Bragg cells at GHz for the first time (paper #6).

This latest AO Bragg cell utilized the ZnO-GaAs composite waveguide structure referred to previously. The center frequency of the SAW was 1.11 GHz. A diffraction efficiency as high as 38% at an acoustic drive power of 2.72mw was obtained. For an incident light propagating in the TE_0-mode, the diffraction efficiency was found to remain constant for the range of input polarization angle up to 35°. The Bragg cell was successfully used to perform light beam deflection/switching and RF spectral analysis (paper #6).

12. Formation of Microlenses and Lens Array in GaAs Waveguide Using Ion-Milling

Lack of waveguide lenses in GaAs has heretofore been an obstacle toward realization of monolithic integrated AO modules or circuits in GaAs substrate. We have, for the first time succeeded in construction of high-quality waveguide lenses in GaAs using ion-milling technique (paper #7). This technique was first successfully experimented with $LiNbO_3$ substrates (paper #8). The technique has proved to be simple and versatile (See paper #9).

GaAs is one of the most promising materials for the monolithic integration of active optical devices including electrooptic and acoustooptic deflector/modulators, lasers, detectors, and optoelectronic devices in a common substrate. Clearly, lenses are among the essential components in such integrated optic modules or circuits, e.g., spectrum analyzers, correlators, and computers. Various types of waveguide lens have been fabricated on a variety of substrates with the exception of GaAs. These lens types include Luneburg, geodesic, index refraction via TIPE or two layers construction, chirp grating, and Fresnel. The material constraints such as a very high refractive index and crystalline properties that associate with GaAs waveguides and the relatively small reduction in refractive index in $Ga_{1-x}Al_xAs$ as a function of x have thus far prevented the first three lens types from being fabricated on them. However, the positive or negative index-changes required in both the chirp grating and Fresnel lenses may be produced through either deposition of a higher-index cladding material, or reduction of the waveguide thickness via etching or ion milling. As a high-quality higher-index cladding material for GaAs is yet to be grown, we have chosen the later technique through ion milling to fabricate the negative-index change lenses. This lens fabrication technique was first successfully applied to lithium niobate substrates to fabricate lenses with high-efficiency and diffraction limited characteristics (paper #8). In a continued effort we have successfully produced single lenses and lens arrays of the types including analog Fresnel, chirp grating, and a hybrid combination of the two in GaAs waveguides, and have obtained equally encouraging results.

Both the analog Fresnel and chirp grating lenses require phase zones with negative index changes from that of the GaAs waveguide. As indicated previously, such phase zones may be readily produced by forming grooves in the GaAs waveguide with ion milling. This approach eliminates the need for a higher-index cladding layer and also reduces the number of fabrication steps to a single masking and then a single etching of the waveguide with the ion mill.

Design parameters and procedures for such negative-index change phase zones have been established (paper #9).

In fabrication, $GaAs/Ga_{1-x}Al_xAs$ waveguide samples with $x = 0.07$ or 0.15 and suitable thickness in the GaAs guiding layer were coated with photoresist, exposed with the phase zone pattern, and milled with argon ion beam to form the lenses desired. The ion-milling facility referred to in Item 5 of Sect. I was used for the fabrication.

In summary, we have, for the first time, realized negative index-change planar waveguide microlenses in GaAs using ion milling. The waveguide lenses that have been fabricated and tested include signal lenses and lens arrays of analog Fresnel, chirp grating, and hybrid analog Fresnel/chirp grating types. We have obtained near diffraction-limited spot sizes (2.49 μm) and high efficiencies (61.5%) in such lenses (paper #9). Ion milling has been shown to be a simple and versatile technique for fabrication of waveguide lenses in GaAs and applicable to any other substrate material such as $LiNbO_3$ (paper #8) and YIG-GGG (paper #10). Such ion-milled waveguide lenses should facilitate realization of a variety of monolithically integrated optic device modules and circuits in GaAs and other related substrates with applications to communications, signal processing, and computing.

III. Journal Publications Generated During Last Program Year

1. P. Le, D.Y. Zang, and C. S. Tsai, "Integrated Electro-optic Bragg Modulator Module for Matrix-Vector and Matrix Multiplications," Appl. Opt., Vol. 27, pp. 1780-1785 (May 1988).
2. C.S. Tsai, "Integrated Optic Device Modules in $LiNbO_3$ for Computing and Signal Processing," Journal of Modern Optics Vol. 35, pp. 965-977, 1988 (Invited paper).
3. C.S. Tsai, D.Y. Zang, and P. Le, "High-packing Density Multichannel Integrated Optic Device Modules in $LiNbO_3$ for Programmable Correlation of Binary Sequences," Opt. Lett., Vol. 14, pp. 889-891 (Aug. 1989).
4. C.S. Tsai, D.Y. Zang, P. Le, "A Novel Scheme for Efficient Excitation of High-Density Channel-Waveguide Array Using Ion-Milled Planar Microlens Array" (To be published in Appl. Opts.)
5. Y. Abdelrazek and C.S. Tsai, "Wideband Acoustooptic Bragg Diffraction in ZnO/GaAs Waveguide at Gigahertz Frequencies and Applications," (To be submitted J. Lightwave Technology for publication).
6. Y. Abdelrazek and C.S. Tsai, "High Performance Acoustooptic Bragg Cells in ZnGaAs Waveguides at GHz Frequencies," J. Optoelectronics - Devices and Technologies, Vol. 4, pp. 33-37 (1989) (Invited paper).
7. T. Vu, J. Norris, and C.S. Tsai, "Planar Waveguide Lenses in GaAs Using Ion Milling," Appl. Phys. Lett., Vol. 54, pp. 1098-1100 (March, 1989).
8. T.Q. Vu, J. Norris, and C.S. .Tsai, "Formation of Negative Index Changes Waveguide Lenses in $LiNbO_3$ Using Ion Milling," Opt. Letts., Vol. 13, pp. 1141-1143 (Dec. 1988).
9. T.Q. Vu and C.S. Tsai, "Ion-Milled Waveguide Lenses an Lens Arrays in GaAs," J. Lightwave Tech., Vol. 7, pp. 1559-1566 (Oct. 1989).
10. T.Q. Vu, C.S. Tsai, D. Young and C.L. Wang, "Ion-Milled Waveguide Lenses and Lens Arrays in YIG-GGG Waveguides," Appl. Phys. Lett., Vol. 55, pp., 2271-2273 (Nov. 1989).

IV. All Publications Resulting From AFOSR Support

A. Earlier Publications

1. C.S. Tsai, D. Young, W. Chen, L. Adkins, C.C. Lee, and H. Glass, "Noncollinear Magnetooptic Interaction of Guided-Optical Wave and Magnetostatic Surface Waves in YIG/GGG Waveguides," Appl. Phys. Lett., Vol. 47, pp. 651-654 (Oct. 1985).
2. C.S. Tsai, D.Y. Zang, and P. Le, "An Integrated Acousto-optic Bragg Modulator in $LiNbO_3$ Channel-Planar Composite Waveguides," Proc. of 5th International Conference on Integrated Optics and Optical Fiber Communication and 11th European Conference on Optical Communication, pp. 125-128, Oct. 1-4, 1985, Venezia, Italy.
3. D.Y. Zang, P. Le, and C.S. Tsai, " An Integrated Acoustooptic Bragg Modulator in a $LiNbO_3$ Channel-Planar Composite Waveguide and Its Applications," IEEE 1985 Ultrasonics Symposium, Technical Digest, pp. 117-118, Oct. 16-18, San Francisco, California.
4. W. Chen, D. Young, and C.S. Tsai, "Mode-Conversion of Guided-Optical Waves Through Noncollinear Interaction with Magnetostatic Surface Waves - Theory and Experiment, " IEEE 1985 Ultrasonics Symposium, Technical Digest, p. 146, Oct. 16-18, San Francisco, California.
5. C.S. Tsai, "Integrated Optic Device Modules for the Space Applications," Proc. of the Society of Photo-Instrumentation Engineers Conference on Optoelectronics and Laser Applications in Science and Engineering, pp. 19-24, Jan. 1986, Los Angeles, California, SPIE, Vol. 616 (Invited paper).
6. C.J. Lii, C.S. Tsai, and C.C. Lee, "Wideband Acoustooptic Bragg Cells in GaAs-GaAlAs Waveguides," IEEE J. Quantum Electron., Vol. QE-22, Special Issue on Integrated Optic Circuits, pp. 868-872 (June 1986).
7. C.J. Lii, C.S. Tsai, and C.C. Lee, "A Compact Miniaturized Acousto-Optic Bragg Cell in GaAs-GaAlAs Waveguides," 1986 Topical Meeting on Integrated- and Guided-Wave Optics, Feb. 26-28, 1986, Atlanta, Georgia, Technical Digest, IEEE Cat. No. 86CH2264-0, pp. 58-59.
8. W. Chen, D. Young, and C.S. Tsai, "Theory and Experiment on Guided-Optical Wave Mode-Conversion Through Noncollinear Interaction with Magnetoostatic Surface Waves in YIG-GGG Waveguides," 1986 Topical Meeting on Integrated- and Guided-Wave Optics, Feb. 26-28, 1986, Atlanta, Georgia, Technical Digest, IEEE Cat. No. 86CH2264-0, pp. 28-31.

9. C.S. Tsai, D. Young, and W. Chen, "Interactions between Optical Waves and Magnetostatic Surface Waves in Ferromagnetic Waveguides," Proc. of International Symposium on Surface Waves in Solids and Layered Structures, Vol. III, pp. 100-115, July 1-4, 1986, Novosibirsk, USSR (Invited Paper).

10. C.S. Tsai, "$LiNbO_3$-Based Integrated Optic Device Modules for Optical Communications, Signal Processing and Computing," 1986 Conference on Laser and Electro-Optics, June 9-13, 1986, San Francisco, California, Technical Digest, IEEE Cat. No. 86CH2274-9, pp. 44-46 (Invited paper).

11. D.Y. Zang and C.S. Tsai, "Titanium Indiffused Proton Exchanged Waveguide Lenses $LiNbO_3$ for Optical Information Processing," Special Issue on Optical Computing, App. Opt., Vol. 25, pp. 2264-2271 (July 1986).

12. C.J. Lii, C.S. Tsai, C.C. Lee, and Y. Abdelrazek, "Wideband Acoustooptic Bragg Cells in GaAs Waveguides," Proc. of 1986 IEEE Ultrasonics Symposium, Nov. 1986, Williamsburg, Virginia, IEEE Cat. No. 86CH2375-4, pp. 429-433.

13. C.S. Tsai, "Titanium-Indiffused Proton-Exchange Microlens-Based integrated Optic Bragg Modulator Modules of Optical Computing," Optical and Hybrid Computing, SPIE, Vol. 634, pp. 409-421, Jan. 1987 (Invited Paper).

14. C.S. Tsai, "Integrated Acoustooptic Device Modules for Communications, Signal Processing, and Computing," 7th Ultrasonic Electronics Symposium, Dec. 8-10, 1986, Kyoto, Japan, to appear in Japanese Journal of Applied Physics, 1987, (Invited paper).

15. D. Young, W. Chen, C.S. Tsai, "Tunable Wideband Guided Wave Magneto-optic Modulator Using Magnetostatic Surface Waves," presented at SPIE Meeting, Jan. 1987, Los Angeles, California, Proc. SPIE, Vol. 753 (Invited Paper).

16. C.S. Tsai, D. Young, W. Chen, H. Glass, and L. Adkins, "Wideband Interactions Between Optical Waves and Magnetostatic Surface Waves in a YIG-GGG Waveguide," Proc. of 1987 International Magnetics Conference, p. GC-07, April 14-18, 1987, Tokyo, Japan (Invited Paper).

17. D.Y. Zang, P. Le, and C.S. Tsai, "Integrated Electrooptic Bragg Modulator Modules for Optical Computing," Second Topical Meeting on Optical Computing, Mach 16-18, 1987, Incline Village, Nevada, Technical Digest Series, Vol. 11, (Optical Society of America) pp. 193-196.

18. C.S. Tsai, "Multichannel Integrated-Optic Device Modules for Optical Processing," 1st International Microoptics Conference, Technical Digest, Tokyo, Japan, pp. 194-185, October 1987 (Invited paper).

19. P. Le, D.Y. Zang, G.D. Xu, and C.S. Tsai, "An Integrated-Optic Digital Correlator Module Using Acoustooptic and Electrooptic Bragg Diffractions in $LiNbO_3$," Proceedings of the 1987 IEEE Ultrasonics Symposium, 87CH2492-7:467-470, October 1987.

20. C.S. Tsai, "Integrated-Optic Device Modules for Computing and Signal Processing," Proceedings of the 21st Annual Asilomar Conference on Signals, Systems, and Computers, IEEE, Pacific Grove, California, pp. 467-473, November 1987 (Invited paper).

21. C.S. Tsai, "Integrated Acoustooptic Device Modules for Communications Signal Processing,and Computing," Japanese Journal of Applied Physics, 26:19-25, 1987 (Invited paper).

22. R.T. Chen and C.S. Tsai, "GaAs-GaAlAs Heterostructure Single-Mode Channel-Waveguide Cutoff Modulator and Modulator Array," IEEE Journal of Quantum Electronics, Special Issue on Electrooptic Materials and Devices, QE-23:2205-2209, December 1987.

B. Publications During Last Program Year

23. C.S. Tsai, D.Y. Zang, and P. Le, "Multichannel Integrated-Optic Device Modules in $LiNbO_3$ for Digital Data Processing," Technical Digest of 1988 Topical Meeting on Integrated and Guided-Wave Optics, Santa Fe, New Mexico, pp. 200-203, March 1988.

24. C.S. Tsai, "Guided-Wave Acoustooptic Devices and Applications," Proceedings of Physics in Microoptics Conference, Tokyo, Japan, pp. 59-70, May 1988 (Invited paper).

25. P. Le, D.Y. Zang, and C.S. Tsai, "Integrated Electrooptic Bragg Modulator Module for Matrix-Vector and Matrix Multiplications," Applied Optics, Special Issue on Optical Computing, 27:1780-1785, May 1988.

26. X. Cheng and C.S. Tsai, "Electrooptic Bragg-Diffraction Modulator in GaAs-GaAlAs Heterostructure Waveguide," Journal of Lightwave Technology, Special Issue on Integrated Optics, 6:809-817, June 1988.

27. C.S. Tsai, "Integrated-Optic Device Modules in $LiNbO_3$ for Computing and Signal Processing," Journal of Modern Optics, Vol. 35, pp. 965-977, 1988 (Invited paper).

28. T.Q. Vu, J. Norris, and C.S. Tsai, "Formation of Negative Index-changes Waveguide Lenses in $LiNbO_3$ Using Ion Milling," Optics Letters, Vol. 13 pp. 1141-1143, 1988.

29. D. Young and C.S. Tsai, "Gigahertz Bandwidth Magnetooptic Interaction in YIG-GGG Waveguide Using Magnetostatic Forward Volume Waves," Appl. Phys. Lett., Vol. 53, pp. 1696-1698, 1988.

30. C.S. Tsai, and D. Young, "Wideband Scanning of Guided-Light Beam in YIG-GGG Waveguide Using Magnetostatic Waves," Appl. Phys. Lett., Vol. 54, pp. 196-198, 1989.

31. T. Vu, J. Norris, and C.S. Tsai, "Negative Index-Change Waveguide Lenses in $LiNbO_3$ Using Ion Milling," Proc. of IEEE/OSA Conference on Lasers and Electrooptics, Nov. 2-4, 1988, Santa Clara, CA, IEEE Cat. No. 88CH2683-1, TuE 6.6, p. 98.

32. T. Vu, J. Norris, and C. Tsai, "Planar Waveguide Lenses in GaAs Using Ion Milling," Appl. Phys. Lett., Vol. 54, pp. 1098-1100 (1989).

33. Y. Abdelrazek and C.S. Tsai, "High Performance Acoustooptic Bragg Cells in ZnO-GaAs Waveguides in GHz Frequencies," J. Optoelectronics - Devices and Technologies, Vol. 4, pp. 33-37, 1989 (Invited paper).

34. C.S. Tsai, D. Y. Zang, and P. Le, "High-Packing Density Multichannel Integrated Optic Device Modules in $LiNbO_3$ for Programmable Correlation of Binary Sequences," Opt. Lett., Vol. 14, pp. 889-891, 1989.

35. T.Q. Vu, and C.S. Tsai, "Ion-Milled Waveguide Lenses and Lens Arrays in GaAs," J. Lightwave Tech., Vol. 7, pp. 1559-1566, 1989.

36. D. Young and C.S. Tsai, "X-Band Magnetooptic Bragg Cells Using Bismuth-doped Yttrium Iron Garnet Waveguides," Appl. Phys. Lett, Vol 55, p. 2242-2244, 1989.

37. T.Q. Vu, C.S. Tsai, D. Young and C.L. Wang, "Ion-Milled Waveguide Lenses and Lens Arrays in YIG-GGG Waveguides," Appl. Phys. Lett., Vol. 55, pp. 2271-2273, 1989.

38. C.S. Tsai, "Guided-Wave Magneto-optic Bragg Cells and Applications," Optics News, Vol. 15, #12, pp. 47-48, 1989 (Invited paper).

39. C.S. Tsai and D. Young, "Wideband Guided-Wave Magnetooptic Bragg Cells with Applications to Communications and Signal Processing," Proc. of 1989 Microoptics Conf., July, Tokyo, Japan, pp. 114-121 (Invited paper).

40. C.S. Tsai, "RF Signal Processing Using Guided-Wave Magnetooptic Bragg Cells," (Proc. of 23rd IEEE Asilomar Conference on Signals, Systems and Computers, Oct. 30 - Nov. 1, 1989, pp. 318-321, IEEE Cat. #89-CH2836-5 (Invited paper).

41. C.S. Tsai, D.Y. Zang, and P. Le, "Multichannel Integrated-Optic Device Modules in $LiNbO_3$ for Digital Data Processing," Technical Digest of 1988 Topical Meeting on

Integrated and Guided Wave Optics, March 28-30, Santa Fe, New Mexico, pp. 200-203.

42. D. Young and C.S. Tsai, "Gigahertz Bandwidth Magnetooptic Interaction in YIG-GGG Waveguide Using Magnetostatic Forward Volume Waves," Technical Digest of 1988 Topical Meeting on Integrated and Guided Wave Optics, March 28-30, Santa Fe, New Mexico, pp. 148-151.
43. D. Y. Zhang, P. Le, and C.S. Tsai, "Integrated Acoustooptic Device Modules in $LiNbO_3$ for Digital Data Processing," Proc. of 1988 IEEE Ultrasonics Symposium, IEEE Cat. NO. 88CH2578-3, p. 451-453.
44. C.S. Tsai, T.Q. Vu, and J.A. Norris, "Formation of Planar Waveguide Lenses and Lens Arrays in GaAs Using Ion Milling," 1989 Topical Meeting on Integrated and Guided-Wave Optics, Technical Digest Series, Vol. 4, (Optical Soc. of America, Washington, D.C. , 1989), pp. 76-79.
45. C.S. Tsai, and D. Young, "Wideband Guided-Light Beam Deflection and RF Spectral Analysis Using Magnetostatic Forward Volume Waves," (Ibid), pp. 29-32.
46. T.Q. Vu and C.S. Tsai, "GaAs Waveguide Lenses and Lens Arrays with Application to Data Processing and Computing," 1989 Topical Meeting on Optical Computing, 1989 OSA Technical Digest Series, Vol. 9, pp. 258-261.
47. C.S. Tsai, D. Young, T. Vu, and C.L. Wang, "Magnetostatic Waves-Based Integrated Optic Device Modules and Applications to Communications and Signal Processing," Proc. of 1989 International Symp. on Microwave Theory and Techniques, Vol. 1, pp. 303-306, IEEE Cat. No. 89CH2725-0 (June 13-15, Long Beach, CA).
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VI. Advanced Degrees Awarded

A. Ph.D. Dissertations

1. C.S. Lii, "Wideband Acoustooptic Bragg Diffraction in GaAs Waveguides," September 1986.
2. W. Chen, "Guided-Wave Acoustooptic Interactions in Spherical Waveguides," June 1987.
3. X. Cheng, "Film Material Characterization and Electrooptic Bragg Modulator," September 1987.
4. D.Y. Zang, "TIPE Microlenses and Microlens Arrays, and Multichannel Integrated Optic Device Modules," October, 1988.
5. Y. Abdelrazek, "GHz Guided-Wave Acoustooptic Bragg Diffraction in ZnO/GaAs/AlGaAs Composite Waveguides and Integrated Optic RF Spectrum Analyzers," September 1989.
6. P. Le, "Multichannel Integrated Acoustooptic Device Modules for Signal Processing, Computing, and Optical Interconnect," December 1989.
7. D. Young, "Microwave Frequency Guided-Wave Magnetooptic Bragg Cells and Applications to RF Signal Processings," December 1989.

B. M.S. Theses

1. J. Norris, "Negative Index-Change Analog Fresnel Lens for Integrated Optics," June 1988.
2. T. Vu, "Negative Index-Change Hybrid Lens of Chirp Grating and Analog Fresnel Types of $LiNbO_3$ and GaAs Planar Waveguides," June 1988.
3. K. Esteghamat, "Guided-Wave Acoustooptic Tunable Filters," November, 1989.
4. A.K. Roy, "Multiport Guided-Wave Acoustooptic Switching Devices," (Expected in April 1990).